The Qualcomm/SnapTrack Wireless-Assisted GPS Hybrid Positioning System and Results from Initial Commercial Deployments

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BIOGRAPHIES

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ABSTRACT
During 2001/2002, several major CDMA-based wireless network carriers deployed Location Based Services (LBS) in Japan, Korea and the USA. The carriers chose Qualcomm's gpsOne^{TM} end-to-end system solution for these deployments. The two main components of the system are Qualcomm's gpsOne^{TM} client implementation and SnapTrack's Position Determination Entity (PDE) server product. The applications range from gaming and personal navigation services to commercial security and Enhanced 911 (E911). It is anticipated that the number of future applications will expand to include a wide range of value added services (VAS).

This paper describes the network architectures, messaging protocols, and positioning measurements used to support these applications. Processing GPS, terrestrial and other measurements concurrently presents several challenges. These complexities and the characteristics of the various measurement types are discussed. Positioning results from actual network data are presented to demonstrate the initial performance achieved.

INTRODUCTION
SnapTrack was formed in 1995 to develop high performance Wireless Assisted GPS (WAG) for E911 applications (see [1] and [2]). In the first few years, the initial concepts and prototypes were developed and tested on all major air interfaces (GSM and IS-95 A/B). In late 1999, the first SnapTrack client/server commercial system was launched in Japan. Qualcomm acquired SnapTrack in the Spring of 2000. This event combined with Qualcomm's gpsOne^{TM} client product release, together with standardization of the over-the-air interface [3] for positioning data in CDMA (Code Division Multiple Access) based wireless telephone systems, paved the way for more commercial deployments of the SnapTrack technology. Since the launch of the first gpsOne^{TM} enabled mobile devices for a personal security application in April 2001 (Secom in Japan), several large wireless

operators have followed with commercial deployments of Qualcomm/SnapTrack gpsOne™ client/server technology. These include KDDI in Japan, SKT and KTF in South Korea, as well as Sprint PCS and Verizon Wireless in the USA.

The applications range from personal security (Secom, KTF) and E911 (Sprint and Verizon), to Location Based Services featuring navigation, gaming, security and fleet management applications (KDDI). Today, many other CDMA wireless network operators are preparing to launch commercial location services utilizing SnapTrack-based Assisted GPS (AGPS) technology. The discussion in the remainder of this paper will focus on the SnapTrack server (PDE) and we will refer to the entire client/server system as gpsOne end-to-end system or simply the gpsOne™ System.

SYSTEM OVERVIEW

As of today (Fall 2002), the gpsOne™ System is deployed in CDMA networks utilizing the following two system architectures:

- User plane
- Control plane

The Mobile System (MS) and Base Transceiver System (BTS) together with Mobile Switching Center/Base Station Controller (MSC/BSC) are common to both architectures. The MS receives GPS and CDMA network measurements and communicates with the PDE via BTS and MSC.

In user plane-based systems (Figure 1), the PDE is interfaced with the Interworking Function/Packet Data Serving Node (IWF/PDSN) to communicate to the Application Server (AS) and MSC/BSC. This architecture uses TCP/IP as a transport layer for IS-801 messages, and is well suited for quick deployment on off-the-shelf Unix platforms. User plane-based systems are currently used by several wireless operators in Japan and Korea as a basis for offering LBS.

In control plane deployments (Figure 2), the PDE communicates with the Mobile Positioning Center (MPC) and MSC/BTS directly. The MPC is responsible to interface with Location Services (LCS). This architecture uses network data burst messaging (DBM) as a transport mechanism of IS-801 and J-STD-036 messages, and it has been exclusively deployed for E911 applications in the USA. The PDE is hosted on a Compaq/HP Himalaya platform.

Depending on the call flow used for communication between the Mobile System (MS) and PDE, the PDE can provide aiding information to the GPS measurement processing of the MS. Acquisition Assistance (AA) and Sensitivity Assistance (SA) data can be sent to the MS, and this information helps to optimize the speed and sensitivity of the search for GPS code phase measurements. In all existing deployments, the smart server (also known as MS-Assisted) mode of operation is implemented either with mobile originated (MO) or mobile terminated (MT) call flows. For both call flows, the navigation solution takes place at the server. This implementation simplifies the requirements for the mobile system, allowing GPS data acquisition to be performed as a background task.

The user plane and control plane architectures in a CDMA-based wireless communication system are illustrated in figures 1 and 2.

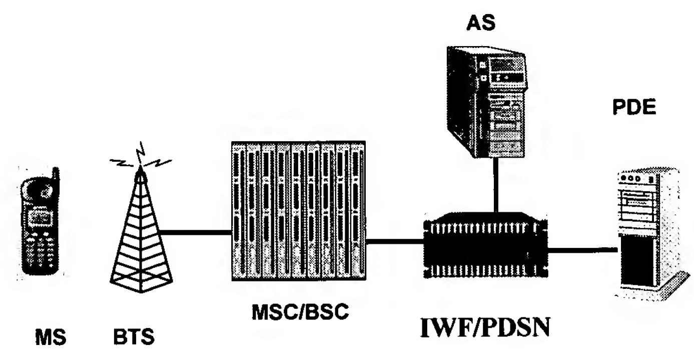

Figure 1. User plane client/server architecture in CDMA network

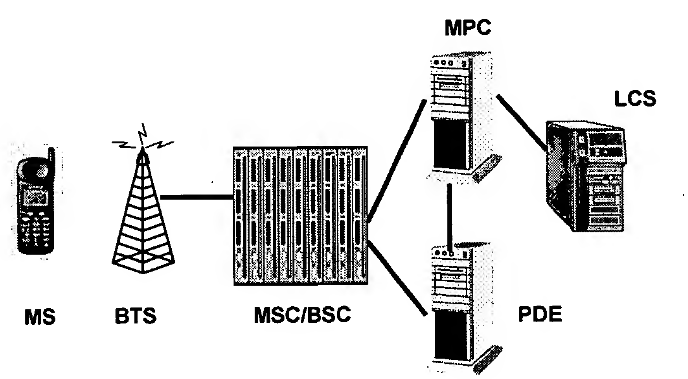

Figure 2. Control plane client/server architecture in CDMA network

The main differences between the user plane and control plane architectures are listed in Table 1.

Table 1 Comparison of User and Control Plane

Architecture	User plane	Control plane
Data Transport	TCP/IP	Data Burst Messaging (DBM)
Application	LBS (VAS)	E911
Platform	Himalaya	Unix
Call flow	Mobile Originated (MO)	Mobile Terminated (MT)
Protocol	IS-801 [3]	IS-801 [3] J-STD-036 [4]
Network Measurement Availability	Pilot Phase Measurements (PPM)	Pilot Phase Measurements (PPM) Round Trip Delay (RTD)

Our experience so far indicates that user plane deployments were generally faster, easier and more streamlined than control plane deployments. Control plane deployments have required updates to several network elements to handle all the standard protocols. Implementation differences between various vendors' network infrastructure were often a cause for delays and complications in the deployment process.

Regardless of architecture choices, the gpsOne™ System discussed above requires two additional system components for operation:

- Wide Area Reference Network (WARN) of fiducial GPS receivers
- Base Station Almanac (BSA)

The WARN is primarily used to provide reference GPS satellite navigation messages for acquisition and sensitivity assistance. The decoded GPS navigation message is used to derive ephemeris, almanac, ionospheric and time corrections for the system, as well as satellite health information. In certain modes, the WARN also provides measurements and consequently differential corrections from the accurately known sites, and these are used for correcting mobile measurements.

The BSA contains information about the terrestrial wireless network. The BSA is used by the PDE to resolve the origin of pilot phase measurements, since IS-95 standard-based CDMA systems only use the pilot pseudonoise (PN) sequence offsets to identify the transmitters.

Both of these data sources (GPS reference network and BSA) are essential for proper operation of current gpsOne™ System deployments.

The following sections contain an overview of the gpsOne™ System and our discussion will be centered on elements of the system that are common to both the user and control plane architectures. Measurement and position types used by the PDE will be explained, and finally, initial results from actual deployments will be presented.

MEASUREMENT TYPES

Several different kinds of measurements may be available to the PDE in different implementations. These can be broken into three broad categories: satellite-based measurements, terrestrial measurements, and other measurements.

The MS acquires satellite-based measurements from Global Navigation Satellite Systems (GNSS). These are primarily GPS measurements, but can also include WAAS, Glonass, and eventually Galileo measurements.

Terrestrial measurements include those acquired by the MS on the forward link from a ground reference station such as a BTS. Terrestrial measurements can also be acquired on the reverse link, measured at the BTS.

Other measurements include altitude aiding, based on a centralized database and/or locally available information, and system specific timing constraints.

Regardless of their origin, all measurements that are part of a given position/velocity request are sent to the PDE for navigation calculations.

Satellite Measurements

The PDE uses GPS as the primary commercially deployed source of satellite measurements. Some of the challenges faced in the use of GPS measurements by an MS are occasional low-signal-strength environments, and high multipath environments.

The MS is frequently used in low-density GPS signal environments, for example indoors in rural, suburban or urban areas. In practice, signal strength may also be lower than an ideal GPS mobile design, because commercial handset form factors and price points may not allow for optimal GPS antenna and front end designs.

Both indoor and outdoor urban environments can impose restrictions on acquiring standard, stable GPS signals due to the presence of significant multipath and high attenuation. To help mitigate these problems, the MS and PDE use techniques of GPS Acquisition Assistance (AA), and Sensitivity Assistance (SA) as defined in the IS-801 standard used in CDMA networks.

Through the use of GPS Acquisition Assistance, the MS can improve the probability of a position fix by performing a concentrated search within GPS code phase windows where the GPS signal is expected. These windows can be set based upon a priori approximate

knowledge of the MS position and uncertainty, such as knowledge that the MS is within the coverage area of a given BTS. These windows can constrain both the Doppler and code phase search space, allowing for reliable acquisition of all GPS signals available.

Another technique used to improve GPS signal strength is coherent integration for more than the traditional 20 ms, the limit imposed by the GPS navigation message data bits transmitted at 50 Hz rate. If the data bits are known in advance, however, the MS can perform coherent integration across data bits, because the effects of the (known) data bits can be reliably removed. The process of providing these data bits to the MS is known as Sensitivity Assistance (SA), and it provides several dB of sensitivity improvement.

Terrestrial Measurements

In addition to the efficient use of GPS signals, strong and weak, the PDE also makes use of a variety of terrestrial measurements. Within the CDMA network, these measurements include coarse and fine pilot phase measurements from legacy and gpsOne™ enabled handsets, respectively. The resolution (precision) of coarse pilot measurements is on the order of 1 CDMA chip (~240 m), while the resolution of the fine pilot phase measurements is 1/16 of a CDMA chip (~15 m). On the reverse link, Round Trip Delay (RTD) measurements are available for both legacy and gpsOne™ enabled handsets via the J-STD-036 interface in the control plane architecture.

With all terrestrial measurements the line of sight is often obstructed, and the signal path between MS and BTS may include many multipath components that are often stronger and significantly longer than the direct path. In some environments the strongest signal path between MS and BTS can sometimes be 1 kilometer or more longer than the direct signal path. Additionally, in some air interfaces, the near-far problem can also be a problem with BTS signals measured at the MS. This problem is also encountered in systems with GPS pseudolites.

Fine pilot phase measurements (PPM) on the forward link are based upon gpsOne™ hardware that has been designed to be more sensitive and accurate than traditional MS communications hardware. This improved hardware can result in 30 dB or more dynamic range in measuring signals from different base stations and this helps to mitigate the near-far problem. Additionally, the measurement processing in gpsOne™ handsets can do more accurate peak location measurement and early peak detection than traditional communications-only handsets.

Coarse pilot measurements (e.g. CDMA one way delay) in legacy handsets are generally less sensitive than gpsOne™ pilot phase measurements, since they have not been specifically tuned for positioning services. As a result, these measurements must be used with even more care.

For both types of pilot measurements, one of the dominant error sources is excess delay (long multipath). Beyond the improvements obtainable through MS hardware and firmware, this error source can also be mitigated through careful use of geometrically redundant measurements (for example from the same BTS, but different sectors). It is also possible to partially calibrate these excess delays, if sufficient data are available in the network over an extended period.

Round Trip Delay (RTD) measurements are, in practice, measurements of the reverse link signal from the MS to the BTS, as measured at the BTS. While this can be thought of as "round-trip" (BTS-MS-BTS) there are usually variable MS timing delays within this signal path that need to be appropriately handled, before the measurement is used. RTD measurements are available in control plane deployments from ground based network elements and can be used to supplement the network provided pseudoranges. In some ways, the RTD measurement can be thought of as a reverse link measurement between MS and BTS that is a geometric duplicate of the forward link measurement. While this does not provide extra physical geometry to the navigation solution, the signal path may be different from the forward link path, due to the use of different forward and reverse link frequencies. Accordingly, this measurement can be used to improve the accuracy of the MS to BTS range/pseudorange estimate. In other ways, the RTD measurement, especially in conjunction with information about MS timing delays, can be used to help estimate the clock state at the MS. Accordingly, this creates an additional measurement to add to the navigation solution.

Other Measurements

Other measurements include altitude aiding and system-based constraints. An altitude-aiding "measurement" (i.e. an altitude estimate) can be provided by the server for an approximately known MS location (for example a BTS coverage area). The PDE can easily be provisioned with an altitude database or derive approximate altitude information from the BSA.

System based constraints include knowledge about the relationship of the MS clock offset to the distance to a given BTS, and knowledge about various forward and reverse link calibrations and their relationships.

Before using any of these measurements in a navigation solution, additional corrections, filtering and weighting is performed to facilitate optimal estimation of positions.

POSITION ESTIMATION

The process of computing a position estimate with varying measurement types and associated geometries is more complex than a typical GPS only navigation solution. On any given request for a position fix, the PDE uses hybrid navigation algorithms to process satellite-based, terrestrial, and other measurements. Not only do these measurements have widely varying error profiles, but they also have varying degrees of linearity and overall reliability.

Another limitation of many wireless mobile positioning implementations is service requirements with very limited time tolerances. The immediate availability of the best possible position solution is critical to many applications, whether the solution is based upon an iterative trilateration approach or other traditional network coverage area-based approaches. Appropriate error models for all measurement types and solution geometries are crucial for producing the best accuracy estimate. Similarly, reliability models are important for providing the highest possible solution integrity.

An additional characteristic of terrestrial measurements in CDMA systems is that there is often an ambiguity in the source of the signal for a particular PN. This ambiguity in BTS identity is resolved by the PDE through iterative methods.

Furthermore, there are often ambiguous solutions to the position solution equations, when terrestrial measurements are incorporated. In these cases, traditional GPS navigation models are inappropriate, since they assume a high degree of linearity. Care must be taken to identify all potential solutions and to eliminate those that have the least probability or seem unreasonable, given a certain network topology, or terrain topography.

In all cases when a sufficient number of redundant measurements are available, fault detection is used to flag outlying solutions, and fault isolation is used too, if possible, remove the offending measurements.

Fault detection, isolation and correction (FDIC) can be challenging in the best-case scenario of accurate GPS measurements, but it is difficult with the mix of measurement types, accuracies, and reliabilities associated with a typical hybrid solution. Traditional approaches are geared towards detecting a single fault, whereas in some measurement environments, excess delay may be the cause of multiple poor measurements. Several specialized algorithms have been employed in the PDE navigation processing to deal with these scenarios.

The gpsOne™ System uses several position determination methods including: cell sector coverage-area based initial position estimation and/or network-based trilateration, coarse GPS acquisition, and more precise GPS acquisition. The goal of navigation processing is to derive GPS positions whenever possible, however, the PDE navigation algorithms keep track of alternative position/velocity estimates obtained during the multi-step process of deriving final coordinates for the user. The reported final position solution is based on the information accumulated during the call flow, and the solution with the best reliability and accuracy estimate is chosen.

OPERATIONAL PERFORMANCE

Deployments both in the USA and in Japan and Korea provide an initial look into the performance of the gpsOne™ System.

From a large sample of live positioning system users making calls from all types of environments, including those areas where no GPS signals can be tracked (such as subway stations), we find that 84% of all fixes are AGPS, 9% are using CDMA fine pilot phase measurements exclusively resulting in Advanced Forward Link Trilateration (AFLT) solutions, and 7% rely on cell sector or enhanced cell sector type positioning. A pie chart showing the distribution of solutions types from live network deployments is shown in Figure 3.

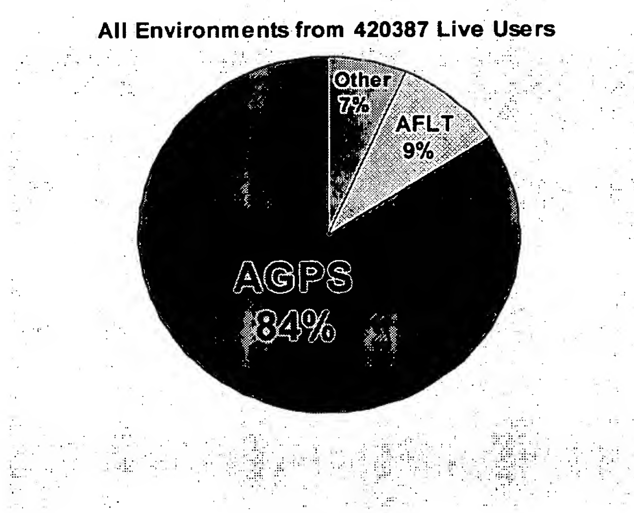

Figure 3. Solution Type Distribution

The strong GPS performance of the gpsOne™ System covering 84% of all position requests from all environment types comes from the ability of the sensor to obtain GPS satellite signals under a variety of difficult conditions with low signal power. This results in 50% of all solutions using more than five GPS satellites. The sensor also has exceptional CDMA fine pilot phase acquisition performance and is able to obtain usable pilot phase measurements at quite low power levels resulting in 50% of all solutions using more than 3 CDMA fine pilot phases. The number of measurements used per fix in

AGPS and AFLT solutions is shown in Figure 4 for the same, large, all environment data set shown in Figure 3.

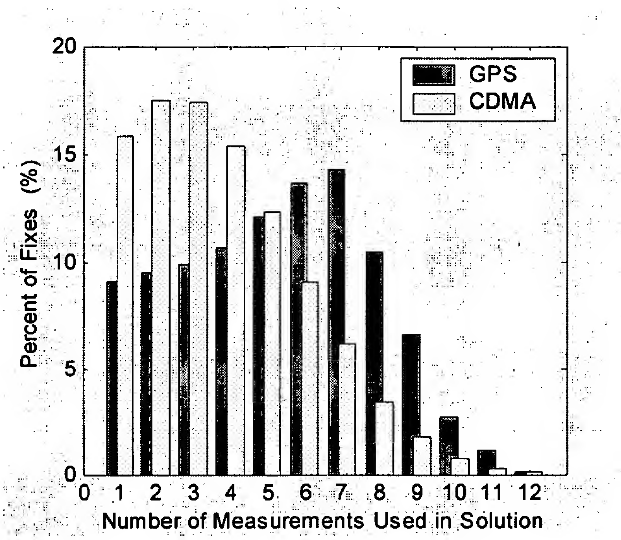

Figure 4. Measurement Count Histogram

TEST EXAMPLE

For tests where the true position of the phone can be determined by external means (GPS receiver, reference survey, etc.) the true accuracy of the location system can be assessed and compared to FCC E911 Phase I type positioning accuracy (see [4] for details).

The following data were collected during a test where three commercial gpsOne™ enabled handsets were used to make a total of 223 location request calls. The calls were made in three different environments: rural, suburban, and urban. The rural environment was an outdoor environment with clear sky view and low topography. In the suburban environment, the calls were made from inside of a wood-frame residence. The urban environment included one and two-story brick and mortar buildings and other reflective objects common to this low-rise city street environment.

Since the true position of the phones was provided using terrestrial surveying techniques, the accuracy of the positioning results can be assessed. The empirical cumulative distribution function (CDF) showing the percentage of fixes with a given horizontal error is shown by the solid line (blue) in Figure 5 for these test data (labeled "Phase II").

The distribution of serving cell sector positions, potentially returned from a E911 Phase I capable mobile system are also shown, using a dashed line (red). The Phase II compliant positions provided by the gpsOne™ System clearly outperform Phase I cell sector center positions in all three environments. In urban settings, the positions based on the serving cell sector may be only hundreds of meters away from the true position, whereas in suburban and rural settings it can be several kilometers away providing a less accurate location for emergency response personnel.

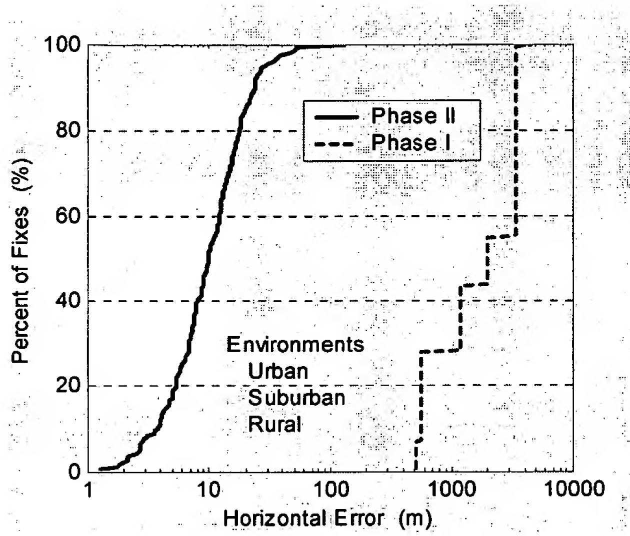

Figure 5. Empirical CDF comparison of gpsOne™ (E911 Phase II) and E911 Phase I results

CONCLUDING REMARKS

The gpsOne™ System was groundbreaking in several markets in the USA, Japan and Korea by providing either Location Based Services or Enhanced 911 services on a commercial scale. The number of users is growing exponentially as shown in Figure 6, and the latest figures through June 2002 show over 3 million gpsOne™ enabled handsets shipped. This is indeed a very exciting moment for those of us deploying this technology around the world.

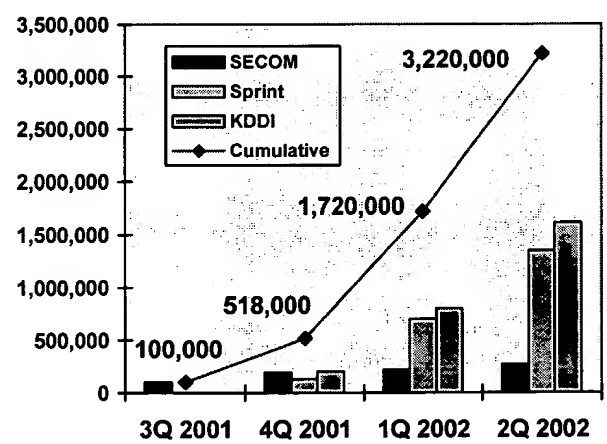

Figure 6. gpsOne™ handsets over the last year (July 2001-June 2002).

System integration for E911 and LBS was often a challenging task in a variety of environments, and Qualcomm and SnapTrack received significant help from our partners, system integrators and operators in various deployments. The data presented in this paper represent only a small fraction of data available today in commercial deployments around the world, and we continue to monitor existing results.

The Qualcomm and SnapTrack teams have an ongoing engineering development program to further enhance the hardware and software in both the client and server implementations to increase yield, accuracy, and reliability of the system. It is very important to recognize that the results shown in this report are from a variety of sources and from mass-market real-world deployments. These results are therefore much more realistic than limited laboratory tests, field demonstrations or general claims made by technology providers without commercial deployments. Thus the performance is a consequence of a multiplicity of environments, sources of imperfections and cost constraints, some of which have been described in this paper.

The results achieved so far show the commercial viability of hybrid positioning with wireless mobile handsets on a large scale and we are confident that further optimization can be achieved, leading to the continued expansion of the commercial applications of this technology.

ACKNOWLEDGMENTS
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